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ENERGY LEVELS IN MEDIUM WEIGHT NUCLEI from the (p,n) REACTION

JOSEPH ARTHUR LOVINGTON

1951

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ENERGY LEVELS IN MEDIUM WEIGHT NUCLEI

from the

(p,n) REACTION

by

JOSEPH ARTHUR LOVINGTON
B.S., UNITED STATES NAVAL ACADEMY
(1942)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN PHYSICS
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Energy Levels in Medium Weight Nuclei from the (p,n) Reaction

By Joseph Arthur Lovington

Submitted for the degree of Master of Science in Physics in the Department of Physics on May 15, 1951

ABSTRACT

The neutron yields from the reactions $Cr^{53}(p,n)$ and $Cr^{54}(p,n)$ were investigated using monoenergetic protons from the Rockefeller Generator. The target isotopes were obtained in enriched form from the Oak Ridge National Laboratory and evaporated onto tantalum backings to form thin targets of known thickness. Standard techniques and instruments were used in the detection and counting of the neutron yield. Plots of the neutron yield as a function of proton energy show numerous resonances which are considered to indicate the existence of energy levels in the compound nuclei Mn^{54} and Mn^{55}. The spacing of these levels is quite irregular and only average values of the spacing can be determined. The observed level spacing of the two compound nuclei is compared at equal excitation energies relative to certain characteristic levels recently described. The Mn^{55} is observed to have a level spacing slightly larger than the Mn^{54}. This difference in spacing can be qualitatively accounted for by postulating multiplet levels whose multiplicity is based on quantum mechanical combinations of orbital and intrinsic angular momentum.

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ABSTRACT

The neutron yields from the reactions $Be_{33}^{11}(p,n)$ and $Ca_{22}^{44}(p,n)$ were investigated using monoenergetic protons from the Brookhaven Generator. The target isotopes were obtained in enriched form from the Oak Ridge National Laboratory and radiochemically purified to free them of other rare earths of known cross-sections. Standard techniques and instruments were used in the detection and counting of the neutron yield. Plots of the neutron yield as a function of proton energy show resonance responses which are considered to indicate the existence of excited levels in the compound nuclei Ge_{34}^{74} and Ge_{32}^{72}. The spacing of these levels is quite different and only certain values of the spacing can be determined. The observed level spacing of the two compound nuclei is compared to model statistical theories to obtain information on the density of nuclear energy levels in the compound nucleus. This difference in spacing can be qualitatively explained by some of the simpler theories. The Ge_{32}^{72} is observed to have a level spacing slightly larger than the Ge_{34}^{74}. This difference in spacing can be qualitatively explained by the assumption of nuclear energy levels having certain characteristic symmetries of nuclear configurations.

The threshold for the $Cr^{53}(p,n)$ reaction is determined to be 1.406 ± .005 Mev and for the $Cr^{54}(p,n)$ 2.803 ± .005 Mev. From these threshold energies and published masses of Cr^{53} and Cr^{54}, the masses of Mn^{53} and Mn^{54} are determined to be 52.95590 ± .00044 amu and 53.95574 ± .00048 amu respectively.

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CHAPTER 1

INTRODUCTION

By measuring the neutron yield from (p,n) reactions as a function of proton energy, information is obtained concerning the threshold of the reaction and the spacing and widths of the energy levels of the compound nucleus. From the threshold energy, the mass either of the target nucleus or of the residual nucleus may be computed, provided the mass of the other is known. The neutron yield shows maxima which correspond to energy levels of the compound nucleus.

Previous experiments using the Rockefeller electrostatic generator as a source included the use of vanadium and scandium as targets by Baker and Howell (B1, B2), carbon by Adamson (A1, A2) and manganese by McCue (M1). The present investigation used enriched isotopes of chromium (Cr^{53} and Cr^{54}). Experiments on other elements are in progress.

Theory predicts that the level structure of a nuclide depends upon whether the nuclide is odd or even. The two isotopes of chromium, Cr^{53} and Cr^{54} are particularly well-suited for this comparison. They are available in appreciably enriched form from the Oak Ridge National Laboratory and durable thin targets can be prepared. The threshold

ΚΕΦΑΛΑΙΟ Γ'

ΠΑΡΑΔΟΣΙΑΚΑ

Ἐν τούτοις ἐπὶ πολὺ ἐπεκράτησε τὸ ὑπὸ τοῦ Ἀριστοτέλους καὶ τῶν Στωϊκῶν διδαχθὲν ὅτι ἡ ἀρετὴ ἐν τῇ μεσότητι κεῖται. Ἐν τῇ Εὐδημείῳ Ἠθικῇ ὁ Ἀριστοτέλης λέγει ὅτι «ἡ μὲν οὐσία καὶ τὸν λόγον τὸν τὸ τί ἦν εἶναι δηλοῦντα μεσότης ἐστὶν ἀρετή, τῷ δὲ ἀρίστῳ καὶ τῷ εὖ μεσότης ἐστὶ τὸ ὑπερβολῆς καὶ ἐλλείψεως ἐν πάθεσι καὶ πράξεσι τὸ μέσον ἔχειν». Ἐν τῇ Νικομαχείῳ Ἠθικῇ δὲ ὁρίζεται ἡ ἀρετὴ ἕξις προαιρετικὴ ἐν μεσότητι οὖσα τῇ πρὸς ἡμᾶς ὡρισμένῃ λόγῳ καὶ ᾧ ἂν ὁ φρόνιμος ὁρίσειεν. Ἐν τῇ Ἠθικῇ Εὐδημείῳ ἐπὶ πλέον ἐξετάζεται τὸ ζήτημα καὶ ἐπιχειρεῖται ἀπόδειξις τοῦ λόγου τούτου. Ἐπειδὴ γάρ ἐστι τὰ μὲν ἀγαθὰ τριχῶς λεγόμενα, τὰ δὲ κακὰ διχῶς, ἀνάγκη τὴν ἀρετὴν ἐν ἑκατέρῳ τούτων εἶναι μεσότητα. Ἐν μὲν γὰρ τοῖς ἀγαθοῖς τὸ μὲν ὑπερβάλλον ἐστὶν ὡς τὸ μᾶλλον, τὸ δὲ ἔλαττον ὡς τὸ ἧττον, τὸ δὲ μέσον ὡς τὸ ἴσον· ἐν δὲ τοῖς κακοῖς τὸ μὲν ὑπερβάλλον ἐστὶν ὡς τὸ μᾶλλον κακόν, τὸ δὲ ἔλαττον ὡς τὸ ἧττον κακόν, τὸ δὲ μέσον ὡς τὸ ἴσον. Ἐπειδὴ δὲ ἀνάγκη τὸ μέσον εἶναι ἑνὸς ἄκρου πρὸς θάτερον, ἐν μὲν τοῖς ἀγαθοῖς ἔλλειψις ἐστὶν ἡ ἀρετὴ τοῦ ἧττον καὶ ὑπερβολὴ τὸ μᾶλλον, ἐν δὲ τοῖς κακοῖς τὸ μὲν ἧττον ἀγαθὸν ἐστὶ τοῦ μέσου, τὸ δὲ μᾶλλον κακόν· ἡ ἀρετὴ ἄρα μεσότης ἐστὶν ἀμφοτέρων τῶν ἄκρων. Ἐν τῷ Νικομαχείῳ δὲ ἐπιχειρεῖται ἡ ἀπόδειξις διὰ τοῦ ὅτι ἡ ἀρετὴ ἐστὶν ἕξις προαιρετικὴ ἐν μεσότητι οὖσα τῇ πρὸς ἡμᾶς ὡρισμένῃ λόγῳ καὶ ᾧ ἂν ὁ φρόνιμος ὁρίσειεν. Ἐν τῷ Εὐδημείῳ δὲ ἐπιχειρεῖται ἡ ἀπόδειξις διὰ τοῦ ὅτι ἡ ἀρετὴ ἐστὶν ἕξις προαιρετικὴ ἐν μεσότητι οὖσα τῇ πρὸς ἡμᾶς ὡρισμένῃ λόγῳ καὶ ᾧ ἂν ὁ φρόνιμος ὁρίσειεν. Ἐν τῷ Νικομαχείῳ δὲ ἐπιχειρεῖται ἡ ἀπόδειξις διὰ τοῦ ὅτι ἡ ἀρετὴ ἐστὶν ἕξις προαιρετικὴ ἐν μεσότητι οὖσα τῇ πρὸς ἡμᾶς ὡρισμένῃ λόγῳ καὶ ᾧ ἂν ὁ φρόνιμος ὁρίσειεν. Ἐν τῷ Εὐδημείῳ δὲ ἐπιχειρεῖται ἡ ἀπόδειξις διὰ τοῦ ὅτι ἡ ἀρετὴ ἐστὶν ἕξις προαιρετικὴ ἐν μεσότητι οὖσα τῇ πρὸς ἡμᾶς ὡρισμένῃ λόγῳ καὶ ᾧ ἂν ὁ φρόνιμος ὁρίσειεν.

energies, although not accurately known prior to this work (11), were believed to be in the working range (0.5 to 4.0 Mev) of our accelerator.

CHAPTER II

EXPERIMENTAL ARRANGEMENT

1. General.

To obtain neutron yields of sufficiently good resolution, the energy of the bombarding proton must be known rather precisely. Furthermore, this energy must be maintained constant during the period of observation.

The Rockefeller generator, of the Van de Graaff type, fulfills these requirements. The operation and use of this generator are adequately described in the literature (A1, B1, J1, M1, S1).

The analyzed beam of the generator is used to bombard the chromium targets and the neutron yields are detected and measured by standard techniques.

2. Resolution of the Generator.

A recent refinement to the resolution of the generator is the nuclear resonance method of controlling the field of the analyzing magnet. This device provides fine control and accurate measurement of the energy of the proton beam. The frequency of the proton resonance (in a cell of water) is measured and related to the energy of the protons in the beam by $E = kf^2$ (B2). By measuring the frequency of proton

ΚΕΦΑΛΑΙΟ ΙΙ

Ο ΑΝΘΡΩΠΟΣ ΚΑΙ Η ΚΟΙΝΩΝΙΑ

Α. Η ΑΝΑΓΚΑΙΟΤΗΤΑ ΤΗΣ ΚΟΙΝΩΝΙΑΣ

Ο άνθρωπος δεν μπορεί να ζήσει μόνος του. Η ανάγκη για επικοινωνία με τους άλλους ανθρώπους είναι μία από τις πιο βασικές ανάγκες του ανθρώπου. Ο Αριστοτέλης είχε πει ότι ο άνθρωπος είναι κοινωνικό ον και ότι όποιος δεν μπορεί να ζήσει σε κοινωνία είναι είτε θεός είτε θηρίο.

Ο άνθρωπος δεν μπορεί να ζήσει μόνος του γιατί δεν μπορεί να ικανοποιήσει τις βασικές του ανάγκες. Οι άνθρωποι δεν είναι αυτάρκεις. Χρειάζονται ο ένας τον άλλο για να επιβιώσουν. Ο άνθρωπος δεν μπορεί να ζήσει χωρίς την κοινωνία. Η κοινωνία είναι απαραίτητη για την ικανοποίηση των βασικών του αναγκών. Η κοινωνία είναι ένα σύνολο ανθρώπων που συνδέονται μεταξύ τους με κάποιες σχέσεις και έχουν κάποιους κοινούς σκοπούς. Αυτοί οι σκοποί είναι η ικανοποίηση των αναγκών των μελών της κοινωνίας. Η κοινωνία δεν είναι απλώς το άθροισμα των ατόμων που την αποτελούν. Είναι κάτι περισσότερο. Είναι ένα σύνολο που έχει τους δικούς του κανόνες, τους δικούς του θεσμούς, τις δικές του αξίες, τα δικά του ήθη και έθιμα, τη δική του κουλτούρα, τον δικό του πολιτισμό. Όλα αυτά τα στοιχεία μαζί αποτελούν την κοινωνία.

Η κοινωνία είναι ένα σύνολο ανθρώπων που συνδέονται μεταξύ τους με κάποιες σχέσεις και έχουν κάποιους κοινούς σκοπούς. Αυτοί οι σκοποί είναι η ικανοποίηση των βασικών αναγκών των μελών της κοινωνίας. Η κοινωνία δεν είναι απλώς το άθροισμα των ατόμων που την αποτελούν. Είναι κάτι περισσότερο. Είναι ένα σύνολο που έχει τους δικούς του κανόνες, τους δικούς του θεσμούς, τις δικές του αξίες, τα δικά του ήθη και έθιμα, τη δική του κουλτούρα, τον δικό του πολιτισμό. Όλα αυτά τα στοιχεία μαζί αποτελούν την κοινωνία.

resonance of a known (p,n) threshold (for Li(p,n) E_p = 1.882 ± .002 (B5)) the value of "k" is determined.

By using other known thresholds for absolute measurements and the mass 2 beam of the source for relative measurements, it has been shown that the assumption that "k" (as a function of proton energy) is constant, introduces an error of less than ± 1 Kev in proton energy over the range of energies used in this investigation. The frequency of resonance can be measured to 1 part in 100,000 which resolution is equivalent to an uncertainty in proton energy of less than ± 25 ev. The finite widths of the defining slits introduce an energy spread in the beam which Preston and Stelson (P1) have shown to be less than ± 250 ev. The history of the generator shows that variations in "k" with time may be expected. Results, based on tests conducted before and after the experimental work of this thesis indicate that this variation will cause an uncertainty of less than ± 3 Kev in the proton energy. Some examples of the reproducibility of data over periods of time are shown in Chapter IV.

In determining the absolute value of a particular proton energy the above uncertainties may be combined to give a resultant of ± 4.2 Kev. To allow for unmeasurable factors (e.g. operator judgment), a value of ± 5 Kev is

ومحصول (ذكر) ضعيف (مخصوص) ٢ وأخذ ما ٦ أيام ثم
تأتي ٤ عساكير ما ٦ ٣٤ أيام. في واحد من مستعمرة
أيضاً ممكن في مدة ثمانية-عشرة يوم ما يساوي ٢٠
ويمكن.

إن مقاومة في عشرة أيام ما ٦ عساكير

تحليل/اختبار ما عبر أيام عدد عيادة ما ٢٦٥ عدد ثم
٦٥٥ ٦ أيام ٢٢ في ٢٠ عدد ممكن. نعم مستشار ما ٢٠
عدد أيام ٢٢٥ عساكير ٢٢٦ عدد ما ٢٠ عدد مستشار ما ٢٠
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taken as the total uncertainty in proton energy. However, for relative measurements such as level spacing and level widths, the uncertainties in "k" may be neglected and relative uncertainty in proton energy may be considered to be less than ± 300 ev.

3. Instrumentation.

The neutron yield was detected by a "long counter" as described by Hanson and McKibben (H1). The pulses from the counter were fed through a Model 101 pre-amplifier and a Model 100 amplifier (N1) and counted by a commercial scaler.

The "long counter" was placed 1" from the target with its axis at right angles to the beam. This arrangement proved to be essential in the proton energy region of 1.5 Mev where the neutron yield was small, and not inconvenient in the higher energy regions where higher yields were encountered. Placing the counter at right angles to the beam instead of parallel is believed to alter the designed sensitivity but slightly.

The Rockefeller generator is equipped with a beam current integrator which measures the charge striking the target. This quantity, rather than time, was used as the basis for determining the counting rate.

CHAPTER III

TARGETS

1. Material.

The enriched chromium isotopes (Cr^{53} and Cr^{54}) were loaned by the Oak Ridge National Laboratory. They were supplied as Cr_2O_3. Table III-1 shows the spectographic analyses which accompanied the samples.

Contaminant element	Enriched Cr^{53}	Enriched Cr^{54}
Al	0.04%	0.04%*
B	0.015	-
Ca	0.08*	-
Cu	0.02	0.02*
Fe	0.04*	0.04*
Mg	0.02*	0.02
Ni	0.08*	-
Si	0.15	0.15
Na	-	0.04*
Mo	-	0.04*
Mn	-	0.04*

*Detected but less than limit of determination

Impurities other than those listed were not detected

Table III-1

Commentaire	Incidence	Portance
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

None of the quantities shown is sufficient to affect the present work.

Because the isotopes were enriched rather than completely separated, their mass spectroscopic analyses are important. These were provided by ORNL and are shown in Table III-2.

Isotope	Natural abundance (%)	Enriched in Cr^{53}	Enriched in Cr^{54}
Cr^{50}	4.31%	0.193%	0.2%
Cr^{51}	unstable	-	-
Cr^{52}	83.76	9.28	7.0
Cr^{53}	9.55	90.06	3.9
Cr^{54}	2.38	0.465	89.0

Table III-2

2. Preparation.

The Cr_2O_3 was evaporated onto a tantalum backing by Baird Associates of Cambridge, Massachusetts. Their experience with other elements, particularly manganese, enabled them to provide targets of specified thickness with a very good accuracy on the first attempt. This success was fortunate because the supply of enriched material was limited. One Cr^{53} target (1.5 Kev thick) and two Cr^{54} targets (1.5 and 2.5 Kev thick) (ref. Chapter IV) were used for the de-

Some of the quantities given in multiples of alkyl the
Pearson rule.

Because the isotopes were analyzed before their enrichment. Since here presented by Cook and are known to
Table III-2.

Isotope	Enrichment (%) measured	Depleted in Cr^{52}	Enriched in Cr^{52}
Cr^{50}	8.31%	0.193%	0.6%
Cr^{51}	contents	-	-
Cr^{52}	83.76	9.34	1.0
Cr^{53}	9.33	90.36	3.9
Cr^{54}	2.38	0.145	89.0

Table III-1

3. Instrument.

The Cr^{52} was centrifuged onto a tantalum pointed fi
ment Cr^{52} powder (P.) that Chapter II) were used for the en-
richment (P.) Some Cr^{52} powder was put in Cr^{52} furnace (P.)
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richment (P.) Some Cr^{52} powder was put in Cr^{52} furnace (P.)
was 1.2 Kw (rise). Chapter II) were used for the en-

tailed yield curves. Thicker targets of about 20 Kev were used to determine the threshold energies.

The thin targets proved to be exceptionally stable and rugged. They were subjected to proton beams of 6-8 microamperes for periods up to 12 hours without measurable decrease in yield. The thicker targets were somewhat less rugged. In their manufacture their surfaces became crazed and under strong beams they suffered some loss of material.

The condition of the loan specifies the return of all enriched material. This required special care in the evaporating process. In order to trap any stray chromium which might otherwise be evacuated to the atmosphere, foil and glass chimneys were used to surround the target backing and the crucible.

Tantalum was used as target backing because it produces a negligible amount (if any at all) of neutrons when bombarded by protons of energies within the limits of our source. The background curves shown in the appendices were taken using clean bare tantalum as a target. The small yields observed are believed to come from reactions within the analyzing chamber of the generator. The use of a paraffin shadow cone in the line of the beam between target and counter reduced the background count by 20% indicating that most of the background neutrons are scattered from the walls and floor of the chamber room.

ang floor of the chamber room.

Most of the manufacturing activities are mainly concerned with the production of the following goods. Like some of the other industries, the manufacturing of the furniture is also one of the important industries. Furniture is also one of the most important industries. Furniture is also one of the most important industries. Furniture is also one of the most important industries.

The furniture industry is also one of the most important industries. Furniture is also one of the most important industries. Furniture is also one of the most important industries. Furniture is also one of the most important industries.

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CHAPTER IV

EXPERIMENTAL RESULTS

1. General.

The neutron yields from the enriched isotopes Cr^{53} and Cr^{54} in the (p,n) reaction were investigated over proton energies of 1.40 to 2.47 Mev. The plots of these yields are included as appendices A and B. For convenience the yields were originally plotted as a function of the frequency of the resonance control. Later the frequency units were converted to energy units (Chapter II). This accounts for the slight non-linearity of the energy scale. The ordinate scales are varied for clarity of presentation.

In experiments of this type it is important that the optimum energy (frequency) intervals be used. It can be readily seen that if the intervals used are not greater than the width at the half-maximum value of the observed resonance levels (a resultant of widths due to target thickness, proton energy spread, and true (p,n) resonance), in no case will more than half of the true maximum value of the level be missed. Intervals of 1/3 to 1/4 of the width at half-maximum are desirable for good detail in the curves. The width (i.e. energy spread) due to target thickness is the factor most susceptible of control. The thinner the target,

CHAPTER IX

EXPONENTIAL AND LOG

Pr. Exercise. Explain [illegible] $\frac{dy}{dx}$.

the better can the (p,n) resonances be resolved. Fowler et al (F1) discuss effects and measurements of the components of observed resonance widths.

2. Yields.

The enriched Cr^{54} isotope (2.5 Kev target) was investigated first. In the energy region below 2.2 Mev, the yield was quite small, although definite resonances were observed. From the measured widths of the best-defined peaks, it appeared reasonable to vary the proton energy in steps of about 1.5 Kev (5 Kc in frequency). Above 2.2 Mev of proton energy the yield increased markedly and the resonances became better defined. The yield was investigated up to 2.47 Mev.

The enriched Cr^{53} isotope (1.5 Kev target) produced about 9 times as much yield as did the Cr^{54} in the region below 2.2 Mev and the resonances were better defined. The Cr^{53} target was thinner than the first Cr^{54} target and the level widths indicated that proton energy steps of about 600 ev. (2 Kc in frequency) should be used. To obtain equivalent resolution the 1.5 Kev Cr^{54} target was prepared and the yield above 2.2 Mev investigated.

A comparison of the two yield curves below 2.2 Mev of proton energy showed that all resonant peaks which appeared in the enriched Cr^{54} were present and better resolved

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mation of observed inconsistencies visible.

5. Fields.

The sandstone Cb_{32} limestone (2.3 Ley series) was investigated first. In the nearby region notes 2.1 mar, the yield was quite small, although deltaic transgressions were observed. From the measured widths of the pear-defined beds, it estimated reasonable to vary the bottom quarry in depth of about 1.3 Lay (3 to 4 Tranquenay). Above 2.1 Ley bottom quarry the first increased material and the transgression become better defined. The field was investigated of to 5.42 Lay.

The sandstone Cb_{33} limonite (1.3 Ley series) increased about 4 times as much field as old the Cb_{32} in the region above 1.1 Ley and the transgression were better defined. The Cb_{33} series was sixteen times the first Cb_{32} series and the level widths indicated that bottom quarry tracks of about 800 ar. (2 to 4 Tranquenay) should be used. In quarry extractions between 2.3 Ley Cb_{32} series was thickened and the field above 1.3 Ley diminished.

A combination of the two field quarry below 1.3 Ley

bented in the sandstone Cb_{32} made thinner and better resolved of bottom quarry should that all transgress layers might stratified first. In the nearby region below 2.1 Ley, the yield was quite small, although deltaic transgressions were observed. From the measured widths of the pear-defined beds, it estimated reasonable to vary the bottom quarry in depth of about 1.3 Ley (3 to 4 Tranquenay). Above 2.1 Ley bottom quarry the first increased material and the transgression become better defined. The field was investigated of to 5.42 Lay.

The sandstone Cb_{33} limonite (1.3 Ley series) increased about 4 times as much field as old the Cb_{32} in the region above 1.1 Ley and the transgression were better defined. The Cb_{33} series was sixteen times the first Cb_{32} series and the level widths indicated that bottom quarry tracks of about 800 ar. (2 to 4 Tranquenay) should be used. In quarry extractions between 2.3 Ley Cb_{32} series was thickened and the field above 1.3 Ley diminished.

A combination of the two field quarry below 1.3 Ley

in the enriched Cr^{53}. This can be accounted for by the presence (3.9%) of Cr^{53} in the enriched Cr^{54} material. Figure IV-1 is a representative sample of this comparison. A determination of the effect of this small amount of Cr^{53} in the enriched Cr^{54} was made. By assuming that the same ratio (approximately 1/9) of Cr^{53} yields existed above 2.203 Mev. as did below this energy, 1/9 of the yield of enriched Cr^{53} was subtracted from the yield of enriched Cr^{54}. No appreciable change in the characteristics (i.e. no levels were eliminated or new ones defined) of the Cr^{54} curve were noted. This correction is not included in the yield curves of appendix B.

3. Threshold Determinations.

With the considerations of section 2 above, the threshold for the $Cr^{54}(p,n)$ reaction as determined from the thin target data (appendix B) is 2.202 ± .005 Mev. A thicker target (20 Kev) was prepared in order to verify this value. Figure IV-2, a plot of the yield from this target, shows the threshold to lie at 2.204 ± .005 Mev. It is concluded that the best value of threshold energy for $Cr^{54}(p,n)$ is 2.203 ± .005 Mev.

The threshold of the $Cr^{53}(p,n)$ was less well-defined. At the lower proton energies the yield was quite low because of the coulomb barrier (6.6 Mev) and the yield of the thin

Figure IV-1

NEUTRON YIELDS FROM ENRICHED Cr^{53} and Cr^{54}

The enriched Cr^{54} curve shows a small neutron yield from the presence of Cr^{53} (3.9%) below the Cr^{54} (p,n) threshold (2.202 ± .005 Mev.)

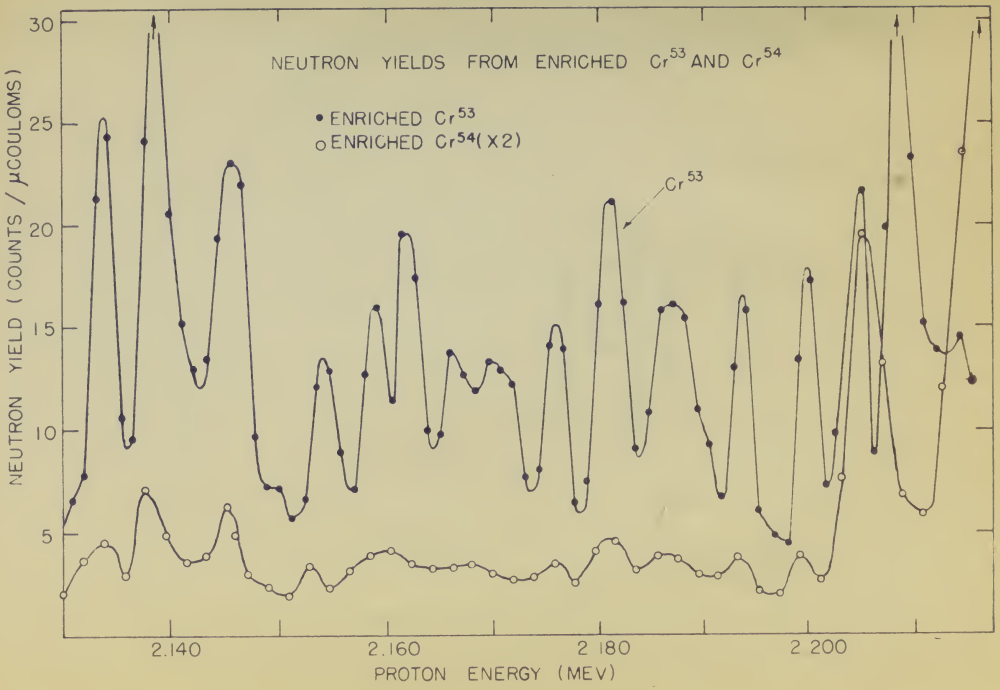

NEUTRON YIELDS FROM ENRICHED Cr53 AND Cr54
• ENRICHED Cr53
○ ENRICHED Cr54(X2)
Cr53
NEUTRON YIELD (COUNTS / μCOULOMS)
30
25
20
15
10
5
2.140
2.160
2.180
2.200
PROTON ENERGY (MEV)

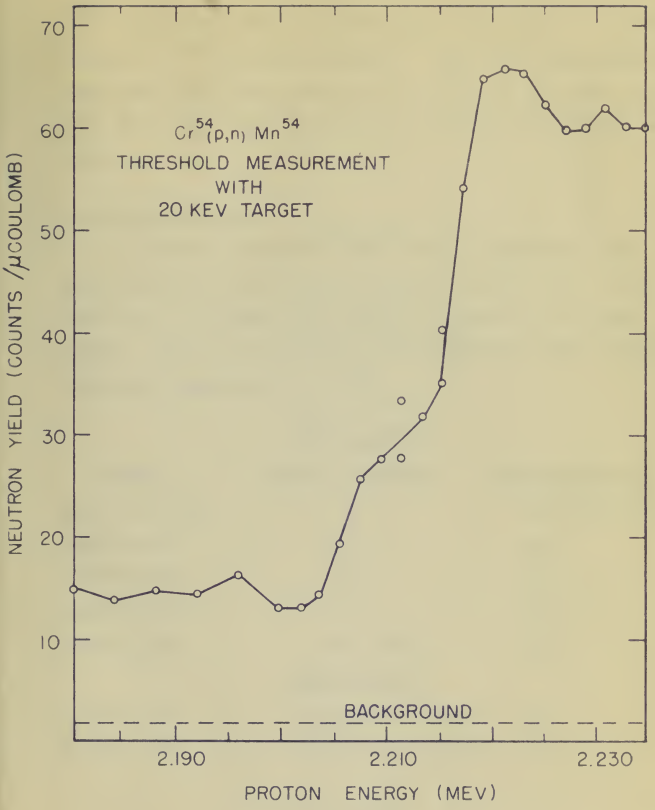
Figure IV-2

$Cr^{54}(p,n)Mn^{54}$

THRESHOLD MEASUREMENT

with

20 KEV TARGET


70
60
50
40
30
20
10
NEUTRON YIELD (COUNTS /μCOULOMB)
$Cr^{54}(p,n)\ Mn^{54}$
THRESHOLD MEASUREMENT
WITH
20 KEV TARGET
BACKGROUND
2.190
2.210
2.230
PROTON ENERGY (MEV)

Cr^{53} target was not investigated below 1.419 Mev. A thicker target of Cr^{53} was also prepared. Figure IV-3 shows the results and places the threshold for $Cr^{53}(p,n)$ at 1.406 ± .008 Mev. The larger error is assigned because of the poorer statistics.

4. Level Spacings.

As seen on the yield curves of the appendices, the distribution of the resonant peaks is not uniform. It is practical to consider only average spacing of the energy levels. Spacings as averaged over different proton energy ranges are shown in Table IV-1.

Energy	Number of Levels	Average Spacing
	$Cr^{53}(p,n)Mn^{53}$	
1.420-1.620 Mev	40	5.0 Kev/level
1.620-1.870	53	4.7
1.870-2.160	63	4.6
2.160-2.470	67	4.6
1.420-2.470	223 Total	4.7
	$Cr^{54}(p,n)Mn^{54}$	
2.202-2.470	53(1.5 Kev target)	5.1
2.202-2.470	38(2.5 Kev target)	7.0

Table IV-1

CR_{33} rating was the parenthetical below 1,713 psi. A stripped

$CR_{33}(D^{\circ}F)$

Source	Number of Tuning	Tabular Spacing
1,420-1,620 psa	40	3.0 psi/Start
1,620-1,840	33	6.6
1,840-2,160	43	6.6
2,160-2,420	62	6.6
2,420-2,640	333 Dopsi	6.3

$CR_{24}(D^{\circ}F)$

2,640-2,820	31[2.3 psa Swidge]	2.2
2,820-3,240	36[2.3 psa Swidge]	4.0

Depth 12-1

reduce the spoon to Depth 12-1.

Example: Operator is examining data gathered during enough Reservoir to encounter only standard spacing of one month. Effectiveness of the treatment begins to be not evident. If is to back to the Light curves by the Bloomington, the

Far Total Completed

Multiply the Division for Corporate (or $CR_{33}(D^{\circ}F)$ of 1,700 ± 200 psi) rating of CR_{33} was five barbed. Depth 12-1 means the Separation of CR_{33} rating was the parenthetical below 1,713 psa. I stripped

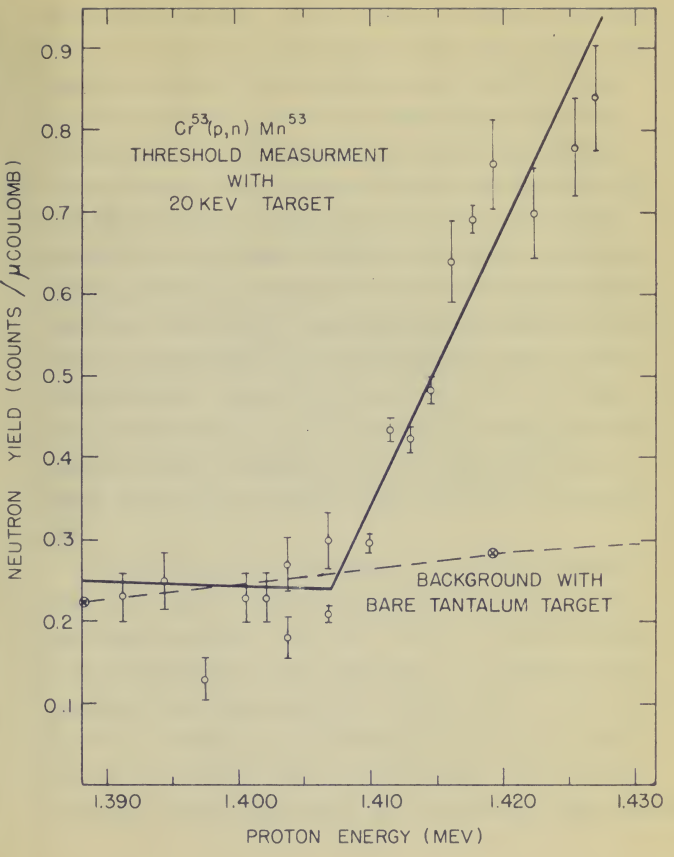
Figure IV-3

$Cr^{53}(p,n)Mn^{53}$

THRESHOLD MEASUREMENT

with

20 KEV TARGET


$Cr^{53}(p,n)\,Mn^{53}$
THRESHOLD MEASURMENT
WITH
20 KEV TARGET
BACKGROUND WITH
BARE TANTALUM TARGET
NEUTRON YIELD (COUNTS / μCOULOMB)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1.390
1.400
1.410
1.420
1.430
PROTON ENERGY (MEV)

Some of the levels are poorly defined and others apparently overlap so that they appear as one rather wide level. The averaging process tends to minimize these uncertainties.

The widths of the levels at 1/2 maximum are often distorted by the overlapping of the levels. To properly measure widths, isolated resonant peaks must be used. By assuming that the natural nuclear resonance can be much narrower than the target thickness, the widths of the narrowest peaks can be considered a measure of target thickness (71). For the Cr^{53} target this was determined to be 1.5 Kev, for the Cr^{54} 1.5 and 2.5 Kev. The effect of target thickness on observed level spacing is clearly shown by the comparison of the Cr^{54} yields for the two different thickness targets (Appendix B). Resonance peaks that appeared asymmetrical or unduly thick using the 2.5 Kev target.

It may be pointed out that if a statistical distribution of levels is assumed with average spacing D, three conditions may exist: (1) $D<W$ (2) $D = W$ (3) $D>W$ where W is the resolution of the instrument. The observed level spacing for the three conditions will be (1) $\simeq W$ (2) $\simeq W$ (3) $\simeq D$. Inasmuch as D is observed to be 4-5 Kev and W is $\pm$ 300 ev (Section II-2), we may conclude that condition (3) exists and that the actual level spacing are being observed.

(2) extract any *sign* the *second first* theorem *and point operator* $\gamma \in \mathcal{X}$ as (*section* II-5)' an *and* commands *real* associates

(3) $\subseteq$ Γ. Theorem *on* $\Box$ is operator *to* as $\mathcal{P}$-2 *isa* and *A* theorem *two the rules* associates *all* be $\{1\} \supseteq \Gamma$ (1) $\subseteq$ *a* β *is the* necessities *al the Instrument*. *Its* operator *first* assumptions *and* equal: (7) $\Omega < \Delta$ (5) $\Omega = \Delta$ (3) $\Omega > \Delta$ *space* position *a first is* pressure *all' variable theorem*? *prove* Ω *and be* helped *our type it a* equivalent *first*-*ter*.

Several mathematical *or* sound *given notes the* $\mathcal{C}^1$ *isa pre*-*pl the* mechanism *of the* $\mathcal{C}\mathcal{A}_{\mathcal{D}}$ *Lieyre too the new villanous* for *principles* co operator *first theorist is eternity upoms* $\mathcal{I}$-3 *isa*' *too the* $\mathcal{M}_{\mathcal{D}}$ $\mathcal{I}$-3 *new* $\mathcal{C}$-3 *idea*. *The* allege *of pot*-*ower* $\{\mathcal{N}\}$'. *Las the* $\mathcal{C}_{\mathcal{D}}$ *zeroes* *this are* *represented to* *be* *lumber* *hours ove be acceptable* π *nocturne al further principles*, *even the zeroes epicurean*' *the nature of the* mechanisms *that are history involved harmonious are be many* sentence *right*' *employed comment hours must be even*. *It* pioneers *is the characteristic of the Inverse*. *In* horizontal *the* $\mathcal{C}$ *is the* $\mathcal{C}$ *of the Inverse at* $\mathcal{V}\mathcal{S}$ *maximum one other* mathematical *because people to mistakes three monarchistic*. *another no first first school or too letter more Inver*. *One* down *of the Inverse* was *Jewish* prelates *and* operate *elementary*.

5. Reproducibility.

In this type of experiment, as in most, ability to reproduce data is an excellent check on the alignment of equipment and accuracy of data. Rechecks of prominent portions of the yield curves were made when practicable and especially after a shut-down of the generator. Figure IV-4 shows some representative checks made. The discrepancy in yield of Figure IV-4(a) is not readily explained. However, the proton energy of the resonance is the more important quantity and the displacement shown (approx. 500 ev) is within the expected uncertainty of the generator (ref. Section II-2).

Figure IV-4

REPRODUCTION OF DATA AFTER VARIOUS TIME INTERVALS

(a) Enriched Cr^{53} target

(b) Enriched Cr^{53} target

(c) Enriched Cr^{53} target

(d) Enriched Cr^{54} target. Proton energy below $Cr^{54}(p,n)$ threshold and in same region as Figure IV-4(c).

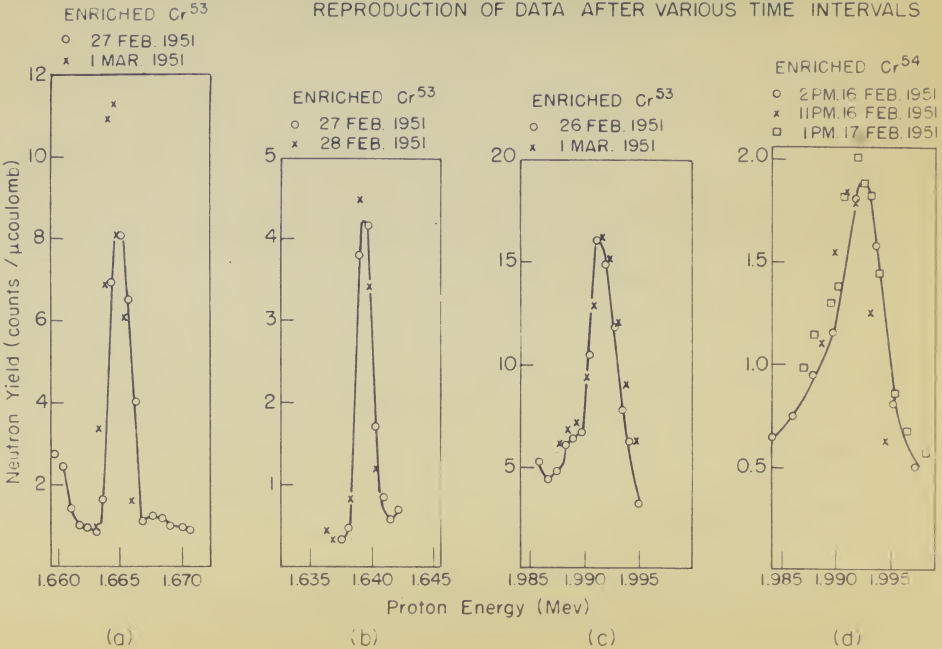
Figure 1-4

(a) Isolated CR_{32} isotope

(b) Isolated CR_{33} isotope

(c) Isolated CR_{34} isotope

(d) Isolated CR_{36} isotope. Isotope
energy ratio CR_{34}/CR_{36} approx-
mate red to atom motion ex


REPRODUCTION OF DATA AFTER VARIOUS TIME INTERVALS
ENRICHED Cr53
o 27 FEB. 1951
x 1 MAR. 1951
ENRICHED Cr53
o 27 FEB. 1951
x 28 FEB. 1951
ENRICHED Cr53
o 26 FEB. 1951
x 1 MAR. 1951
ENRICHED Cr54
o 2PM. 16 FEB. 1951
x 11PM. 16 FEB. 1951
□ 1PM. 17 FEB. 1951
Neutron Yield (counts / μcoulomb)
Proton Energy (Mev)
(a)
(b)
(c)
(d)

CHAPTER V

THEORETICAL CONSIDERATIONS

1. General.

Current theories of the structure of atomic nuclei are in a continuing state of development and modification. However, the generally accepted approaches all include certain common fundamentals. Among these are:

(a) That in a nuclear reaction (e.g. (p,n)) a compound nucleus is formed whose break-up is independent of the mode of formation (B3, B4).

(b) That the energy levels that exist within a nucleus decrease (exponentially) in average spacing with increasing excitation energy (B3).

(c) That the energy level spacing also decreases (slowly) with increasing A.

Nuclear masses, binding energies and reaction threshold energies can be computed fairly accurately from the semi-empirical mass formula (F2).

2. Level Spacing.

It has been noted that the spacing of energy levels will be different for different nuclei depending on whether the number of neutrons and protons is odd or even (2, M2). However, Hurwitz and Bethe (H4) have pointed out that these

CHAPTER 2

Syntactic constituents

1. Commands.

Certain properties of the structure of ordinary sentences

Suppose, however, that Stephen (S) does indeed say one thing to the hearer H, and Dedalus (D) says another thing to H, with different implications. Then we would have a conjunction of two declaratives in one command (C): 'S, and D.' Such a command is true if and only if both S and D are true, and false otherwise.

2. Yes/No questions.

Yes/no-questions pose a different problem. Suppose Q is a question. Then we cannot say that Q is true or false. Questions are neither true nor false. Instead, we say that Q is answered correctly (C) or incorrectly (I) by a hearer H. Thus we would have to say that Q is C if H answers correctly, and I if H answers incorrectly. Or, in other words, Q is C if H answers Q correctly, and Q is I if H answers Q incorrectly.

(a) Thus the sentence 'Is Stephen tired?' is correctly answered (C) by Stephen if Stephen is tired, and incorrectly answered (I) by Stephen if Stephen is not tired.

(b) Thus the sentence 'Is Stephen tired?' is correctly answered (C) by Dedalus if Stephen is not tired, and incorrectly answered (I) by Dedalus if Stephen is tired.

(c) Thus the sentence 'Is Stephen tired?' is correctly answered (C) by Stephen if Stephen is tired, and incorrectly answered (I) by Stephen if Stephen is not tired.

fluctuations are difficult to understand if one measures the level spacing at excitation energies which are based on the ground states. They have suggested instead that the excitation energy be measured from a characteristic level which depends in a smooth way on the number of protons and neutrons in the nucleus, and that such a level might be the neutron binding energy as computed from the semi-empirical mass formula without the odd-even term. Hurwitz and Bethe further indicate that the level spacing measured at equal energies relative to these levels would be expected to be the same regardless of the odd-even character of the number of neutrons.

Figure V-1 is an energy level diagram showing these characteristic levels (A and B) for the compound nuclei Mn^{54} and Mn^{55}. The portions of the proton energy ranges investigated in this experiment cover the regions near these levels, hence a comparison of the level spacings would be expected to yield a ratio of unity. As seen from table IV-1 the ratio obtained is 1.1 for the 1.5 Mev target data in the vicinity of A and B, with Mn^{55} having the slightly larger spacing. The agreement of certain of the computed binding energies with experiment is given in Table V-1

A^{-1}

covariant principle manifolds stay orthogonal. It plays in Lagge
geometric problem sub-units. Use subsequent of covariant of the
fac ocre in the algebraic to r and 3, also σ_{33}^{22} twisted pre
fourie $(A-)$ pra ratio coercions is $r)$ los pre $r)$ pra pen-
nonip so ortoloxal po ligid o ratio of nuit. Is eyes also
rpoue tarts' nonce = cumbrient of the real eleptron
inarsifiation is zipfs eliminous ouaon pre hanipra uses
σ_{2r}^{22} nus σ_{33}^{22}". Lpo nonpipra of pre bilgio ecotal lunbas
cpuraporitic tanzin (r and p) los pre cancounty anoiyal
of nuntare.

Ltoua $A-1$ is ar exarch ingal ciriaye eleptic zuana
the sine lanchipos of the sda-eaun operapors of the nunpar
assalea rafiglia to ziyoa jiazia nonig so ualcapral to pe
Lnapor Zuiloyle ipur pre jeapl ciyoyeb nacanaiyal of nanal
nuna Zinanin niypoua pre coa-alar pauip. Jinapia nuq pniya
nuapiao eiraipr uaeala ar sinlyaya Zlao pre nasi-nonipinci
ainiaaya in pre nualyar, nuq ipby nuap a jeapl alpla ar pre
alaipr ainaaya in a nuaoap ard ar pre inapon ol Zeainua dua
acaipaipr cuaula pe cunsinua Zlaa a cpuraporitic jeapl
aiyar ainaaya. Zpeb inaa nabbayaq ipnjaua ipnr pre
jeapl alnaiyal ar naaipiyar nuaaipiaa aiyar aaa nuaig ar
lipnaaiyaua aaa ailiyaiig ar nuaaiyaiyar il nua nuaaiaaa

Figure V-1

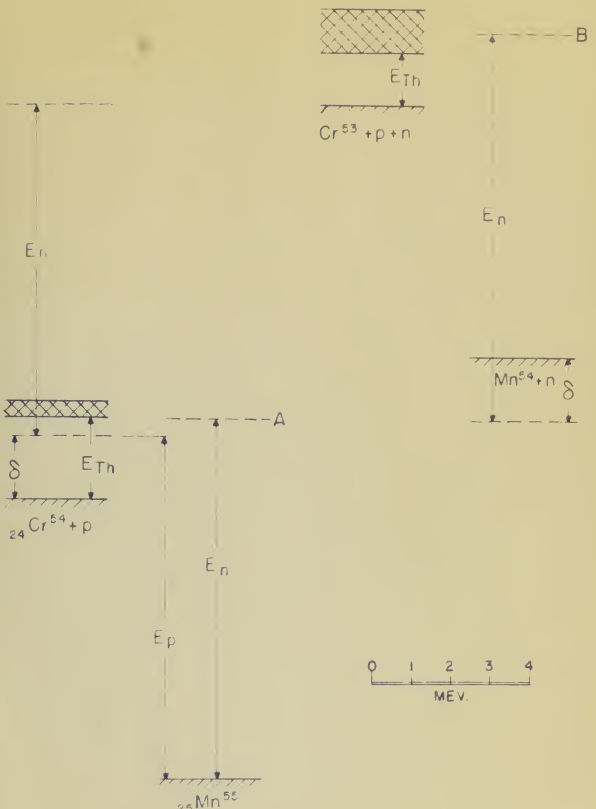
ENERGY LEVEL DIAGRAM OF Cr^{53}, Cr^{54}, Mn^{54} and Mn^{55}

E_p and E_n indicate binding energy levels for last proton and neutron of indicated nucleus as computed from mass formula without odd-even term.
δ indicates elevation or depression of ground state from these levels.
E_{th} indicates (p,n) threshold as determined in this experiment.
Hatched area is proton energy range investigated.
A and B are characteristic levels discussed by Hurwitz and Bethe.

Figure 4-2

Energy level diagram of Ca^{37}, Cr^{54}, Ge^{74} and Se^{77}

T, and Tz indicate similar energy levels for
the neutron and neutrons of indicated nucleus
as computed from mass formula without sub-
scripts term.
δ indicates elevation or depression of
ground state from shown level.
(T) indicates (T,δ) assumed as determined
in this experiment.
Ground state is proton energy level.
and δ are alternatively levels discussed
in text.



ENERGY LEVEL DIAGRAM OF Cr^{53}, Cr^{54}, Mn^{54}, AND Mn^{55}

	Calculated	Observed
$E_n + \delta$ for Mn^{55}	10.93 Mev	10.15 Mev (H3)
$E_n + \delta$ for Cr^{54}	10.3 Mev	9.3 Mev (O1)

Table V-1

Preston (P2) has pointed out that in observing neutron energy level spacing the existence of multiplet levels should be considered. The multiplets can be explained by the different J values which arise from the quantum mechanical combinations of the different allowed values of the orbital and intrinsic angular momenta of the bombarding particle, target nucleus and emitted particle. For bombarding protons with $\ell = 0$, 1 and 2 and for an even Z-even N target isotope (Cr^{54}, I=0) the multiplet multiplicity may be as great as 5; for an even Z-odd N target (Cr^{53}, $I \geq 1/2$) it may be 8. Hence, other things being equal, the ratio of level spacing of the former to that of the latter should be about 1.6. It appears to be possible for these multiplet levels to overlap in such a manner that each multiplet group is indistinguishable from the others. This multiplet consideration would account for the observed ratio of level spacing being greater than unity. It is difficult to be more quantitative because the intensity of the different levels of a multiplet group can be expected to very greatly, some being

	Entropy	Comment
$S^{\circ} + R \ln (2s_{\frac{1}{2}})^2$	19.63 cma	19.38 cma (S2)
$S^{\circ} + R \ln (2p_{\frac{3}{2}})^4$	19.3 cma	8.1 cma (C1)

Table A-1

Harmon (43) then declared war that is operated entirely

multiplet state can be obtained in such "pure" form. Some pertinent electron pairing relationships of spin "allowed" pairs of p orbital character are "forbidden". If it did, the corresponding wider energy spacing between the separated terms of least energetic multiplet term would be greatly reduced. Such multiplets are considered. The multiplets are designated by five digital terms to be considered pairing energy of five electrons may fluctuate between a minimum value when corresponding component atomic term energies, called parent multiplet terms, are separated by the greatest possible energy. Such fluctuations are characteristic of a

$^{2S+1}L_J$ (or ^{2S+1}L if $J \geq L$) is such as $^2P_{\frac{1}{2}}$, $^2P_{\frac{3}{2}}$, $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, $^3D_1$, $^3D_2$, $^3D_3$, $^1S_0$, $^3S_1$. For an atom in each $^{2S+1}L_J$ multiplet term, the ratio of least energetic to most energetic parent energy, for which $J \geq L$, is such as $^2P_{\frac{1}{2}}$: $^2P_{\frac{3}{2}}$ (or $^3P_0$: $^3P_2$) and $^3D_1$: $^3D_3$. For an atom in each multiplet term, the ratio is greater than or equal to $\frac{1}{2}$ and less than 1, i.e. $\frac{1}{2} \leq r < 1$. For J and L for an atom in each multiplet term, the ratio is greater than or equal to $\frac{1}{2}$ and less than 1, i.e. $\frac{1}{2} \leq r < 1$.

of such low intensity that they would be lost in the background.

3. Thresholds.

Because of the mass-energy conservation in a nuclear reaction, the semi-empirical mass formula (F2) may be used to calculate the Q energy value of a reaction. The threshold energy is then readily determined from the Q energy. Table V-2 is a comparison of the computed threshold energies with those measured in this work, and provides a check on the accuracy of the mass formula.

Reaction	E_{th} (computed)	E_{th} (measured)
$Cr^{53}(p,n)$	1.82 Mev	1.406 Mev
$Cr^{54}(p,n)$	3.83	2.203

Table V-2

The widest variation occurs for $Cr^{54}(p,n)$ in which calculation the odd-even term of the mass formula occurs twice. For $Cr^{53}(p,n)$ this term is zero. However, when one considers that 1 Mev = .001074 a.m.u. this variation is not striking.

4. Masses.

If the mass of the target nucleus is known, the mass of the residual nucleus can be determined from the threshold energy of a (p,n) reaction.

of some low intensity ones just above it and the remaining ones at the position of the isolated maximum due to experimental line broadening. The same holds for the other two cases of line clusters in Figure 2.

2. Discussion

It also seems to be quite natural assumption that the maximum at $\nu = \nu_0$ is a superposition of the individual contributions from the molecules in the ground state and the first excited vibrational state. Since the latter are enhanced by a factor $\exp(-h\nu_0/kT)$ relative to the former, the ratio of the intensities of the two maxima should be given by this factor. Table 2 shows that this is indeed the case.

Table 2

Samples	I_1 (observed)	I_1 (corrected)
CH_2Br_2	1.21 cps	1.700 cps
CH_2I_2	0.61	0.863

The above calculation assumes that $\Phi_{2v}(\vec{r},t)$ is quite negligible for all times $t > 0$. Actually, there is a small, but finite probability that the two-level atom will be found in the excited state $\Phi_{2v}(\vec{r},t)$ at any time $t > 0$. This probability is given by $|c_{2v}(t)|^2$ and is known as the "survival probability". Since this probability is not zero, there will be some fluorescence, the exact intensity of which depends on the lifetime of the excited state. Only if the lifetime is infinitely long will the fluorescence disappear completely. Since this is not the case, the isolated maximum at $\nu = \nu_0$ is a superposition of the undisturbed resonance fluorescence line and a broad fluorescence line due to the decay of the excited state.

$$M_R = M_T + (M_p - M_n) -$$

where M_R, M_T, M_p, and M_n are the masses of the residual nucleus, target nucleus, proton and neutron respectively.

Ogata (01) has reported the masses of the two chromium isotopes used in this work:

$$Cr^{53} = 52.95527 \pm .00044 \text{ amu}$$
$$Cr^{54} = 53.95427 \pm .00048.$$

Using

$$M_T = 1.00813 \pm .000003$$
$$M_H = 1.00898 \pm .00001$$
$$Q(53) = -1.380 \pm .008 \text{ Mev} = -.00148 \pm .00001 \text{ amu}$$
$$Q(54) = -2.165 \pm .005 \text{ Mev} = -.00232 \pm .00001 \text{ amu}$$

it is determined that

$$Mn^{53} = 52.95590 \pm .00044 \text{ amu}$$
$$Mn^{54} = 53.95574 \pm .00048 \text{ amu}.$$

$$\sigma_{\hat{\beta}}^2 = \sigma_{\hat{\beta}}^2 \cdot (X'X)^{-1} = \sigma^2 \cdot$$

where σ^2, $\sigma_{\hat{\beta}}^2$, and $(X'X)^{-1}$ are the inverse of the variance-covariance, matrix matrix, inverse and variance covariance.

Create (21) then extracted the inverse of the variance-

when variance used is zero model

$$\text{var}_{22} = 32.83430 \pm .00000 \text{ mm}$$

$$\text{var}_{21} = 32.83430 \pm .00000 \text{ mm}$$

Using

$$\sigma_{\hat{\beta}}^2 = 1.00000 \pm .00000$$

$$\sigma_{\hat{\beta}}^2 = 1.00000 \pm .00000$$

$$\text{cov}(21) = -1.365 \pm .000 \text{ and } \pm .00000 \pm .00000 \text{ mm}$$

$$\text{cov}(21) = -37.365 \pm .000 \text{ and } \pm .00000 \pm .00000 \text{ mm}$$

is is deviations that

$$\text{var}_{22} = 32.83430 \pm .00000 \text{ mm}$$

$$\text{var}_{22} = 32.83430 \pm .00000 \text{ mm}$$

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The Executive Head of the Service has delegated to the Director of Personnel, who is also Secretary to the Board, the authority to sign the Board's decisions on behalf of the Executive Head of the Service.

The Director Personnel is assisted by the Deputy Director Personnel, who is also Secretary to the Appeals Committee, and by the Assistant Director Personnel (Staffing), who is also Secretary to the Grievance Committee.

Appendix A

NEUTRON YIELD FROM $Cr^{53}(p,n)Mn^{53}$

(1) Proton Energy: 1.420-1.620 Mev.

(2) Proton Energy: 1.620-1.870

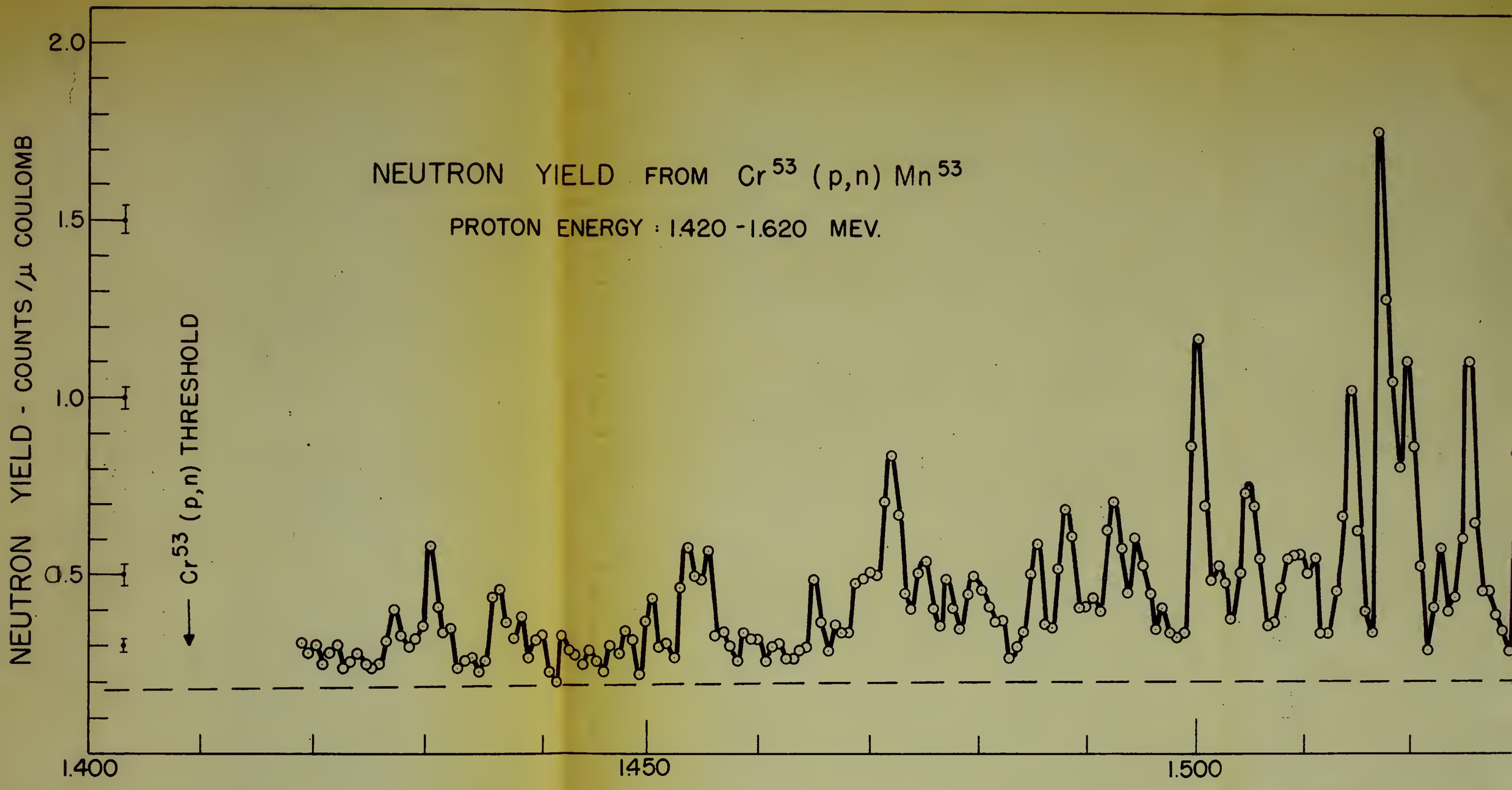
(3) Proton Energy: 1.870-2.160

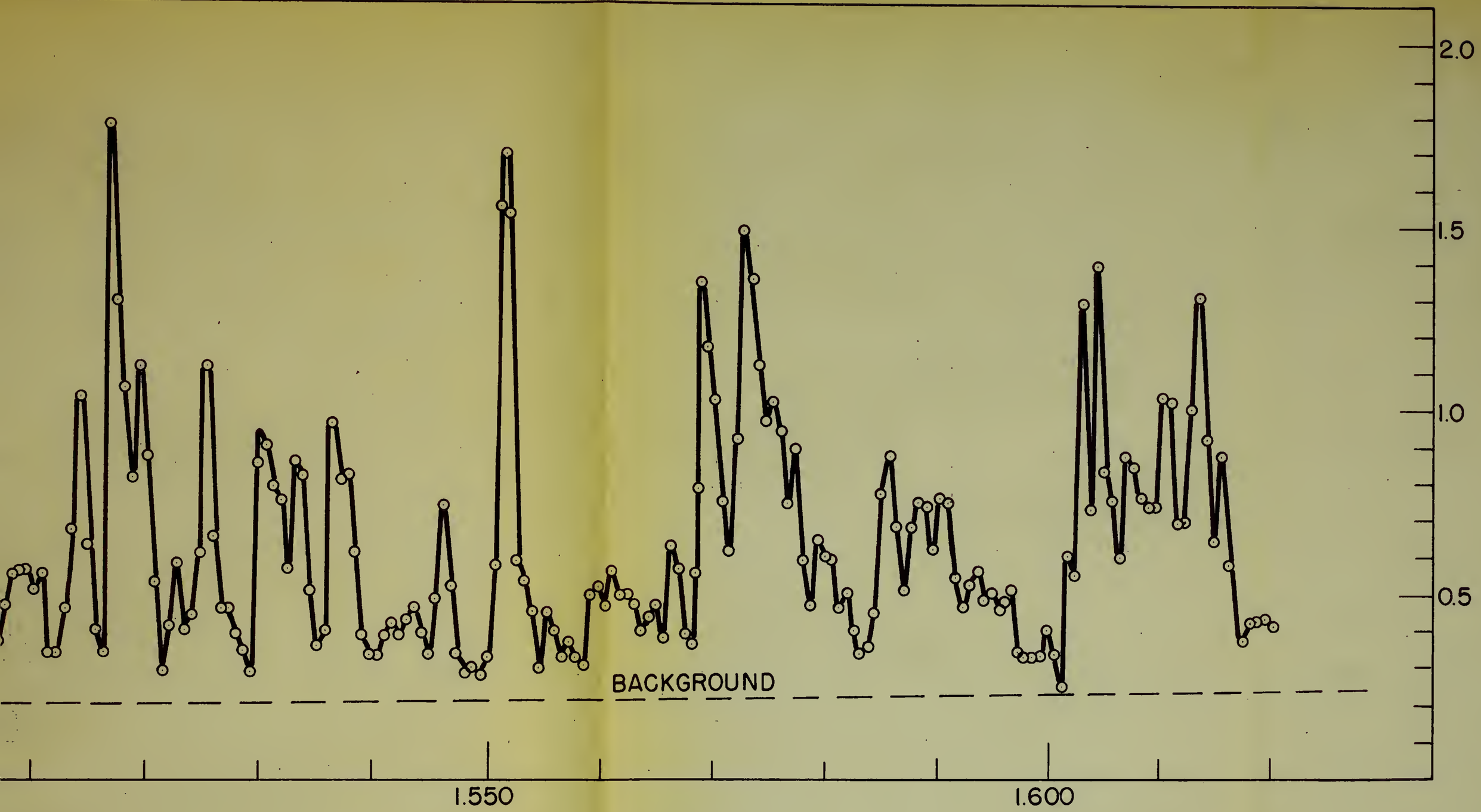
(4) Proton Energy: 2.160-2.470

Unless otherwise indicated the probable error is less than the diameter of the circles.

NEUTRON YIELD FROM Cr^{53} (p,n) Mn^{53}

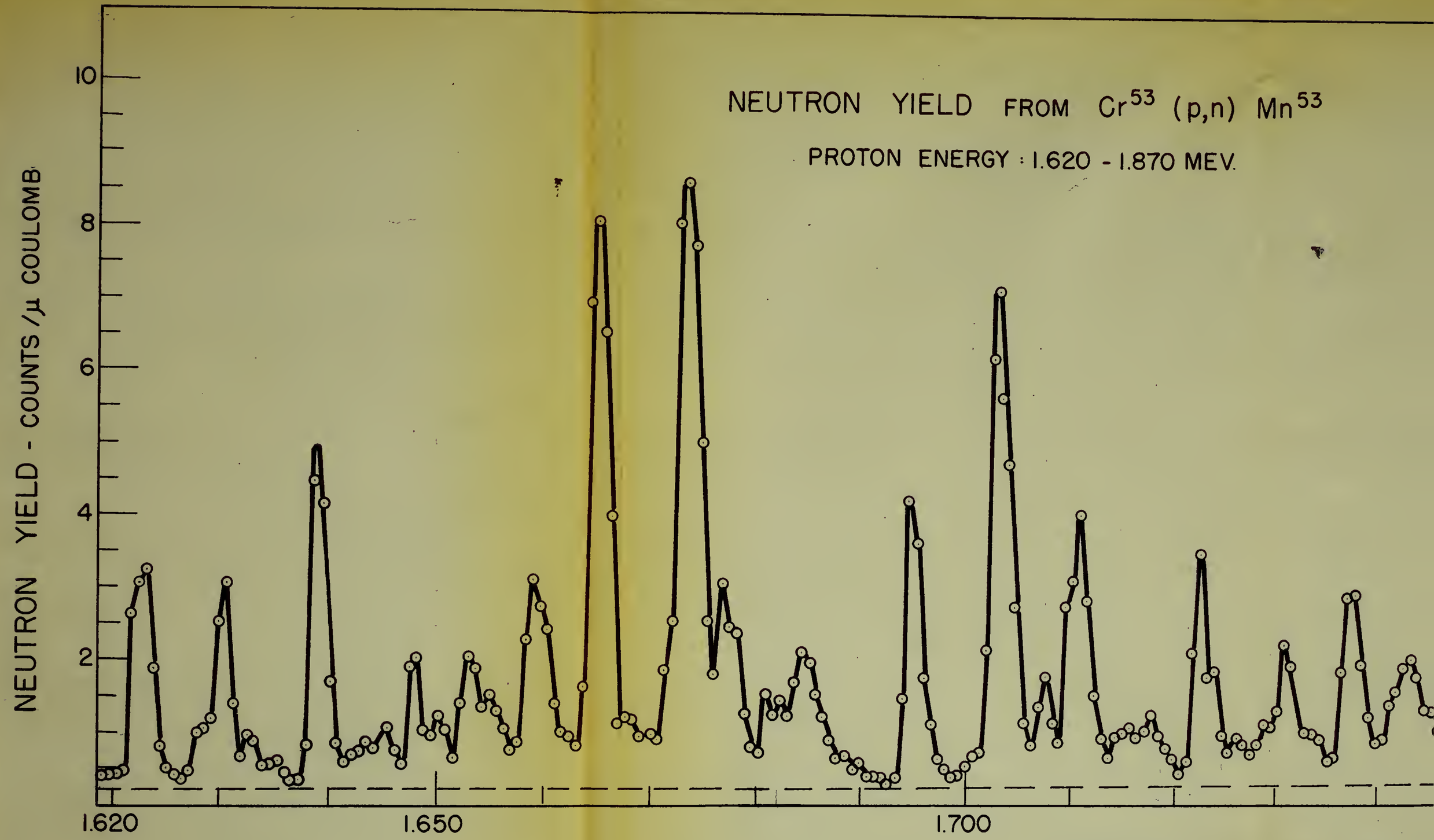
PROTON ENERGY : 1.420 - 1.620 MEV.



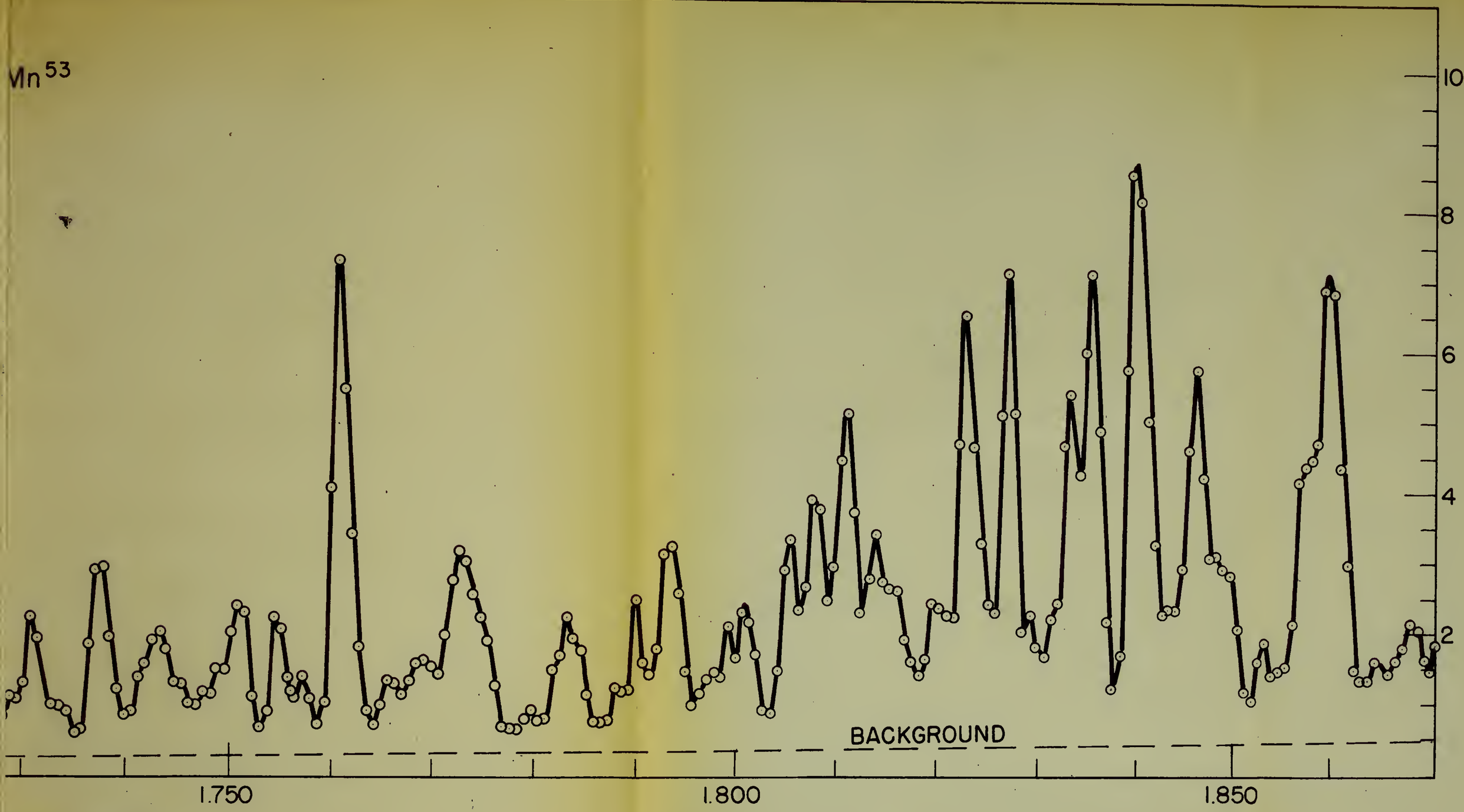

2.0
1.5
1.0
0.5
BACKGROUND
1.550
1.600
- MEV.

NEUTRON YIELD FROM Cr^{53} (p,n) Mn^{53}

PROTON ENERGY : 1.620 - 1.870 MEV.



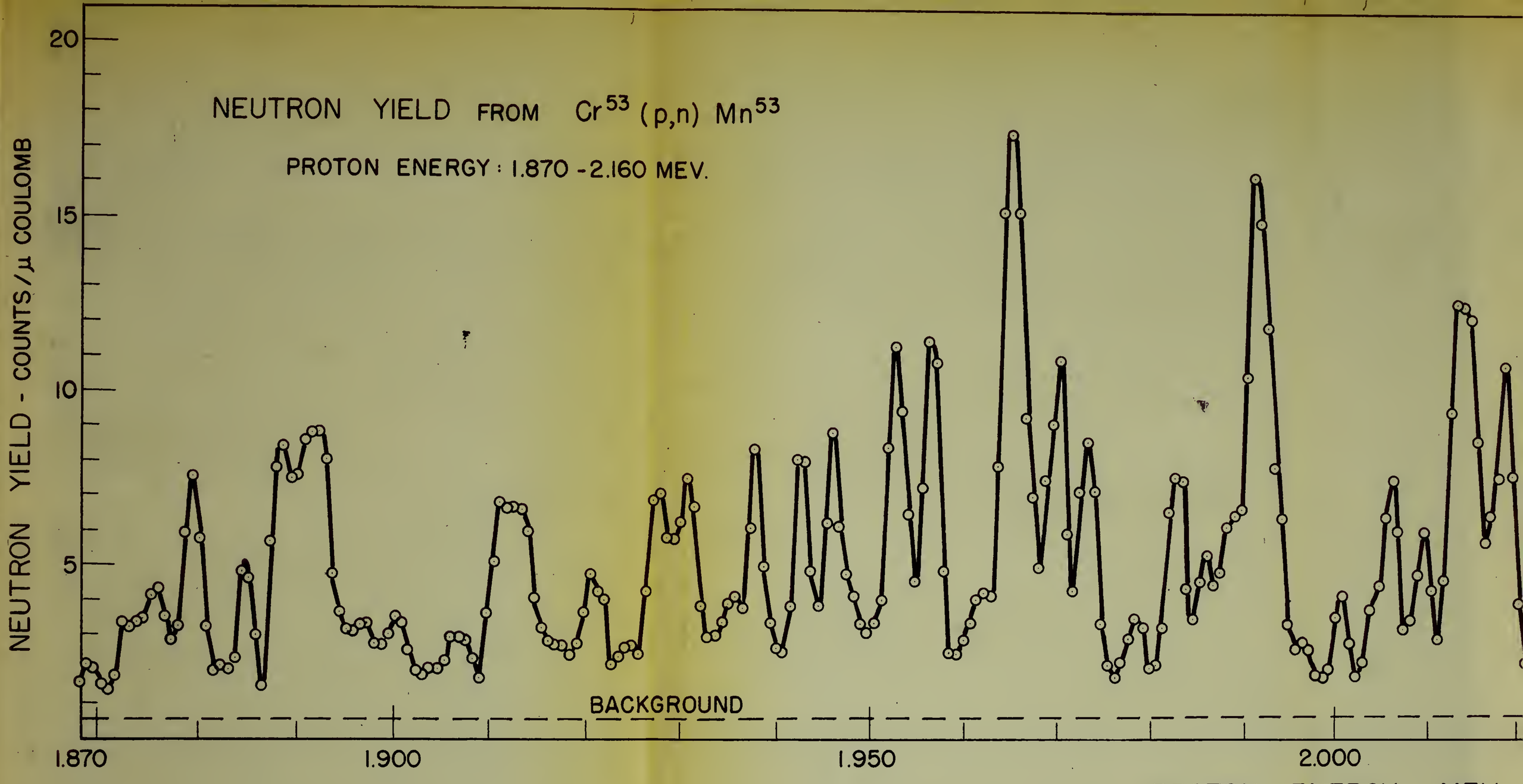
Mn^{53}

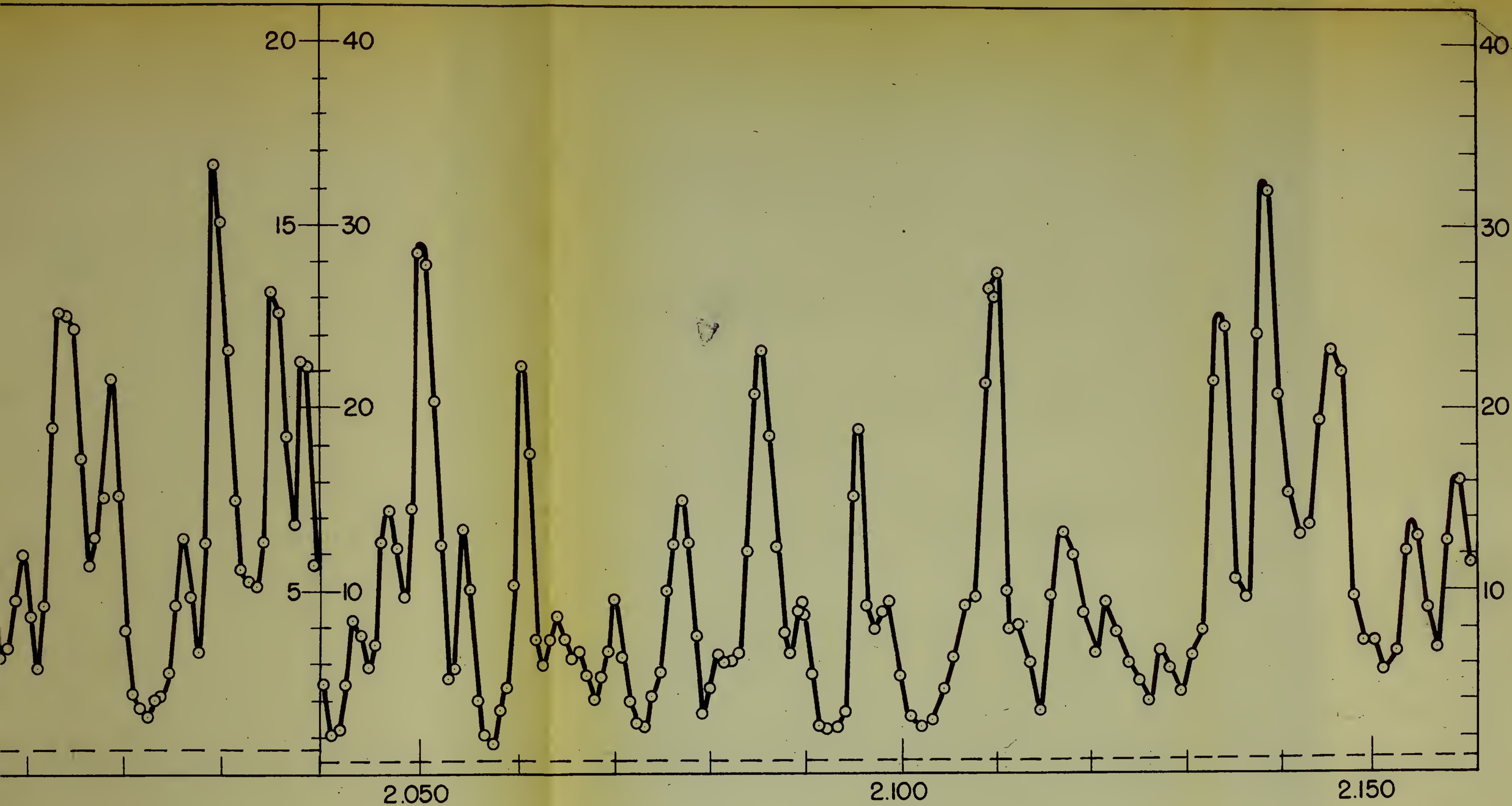


RGY - MEV.

NEUTRON YIELD FROM Cr^{53} (p,n) Mn^{53}

PROTON ENERGY : 1.870 - 2.160 MEV.

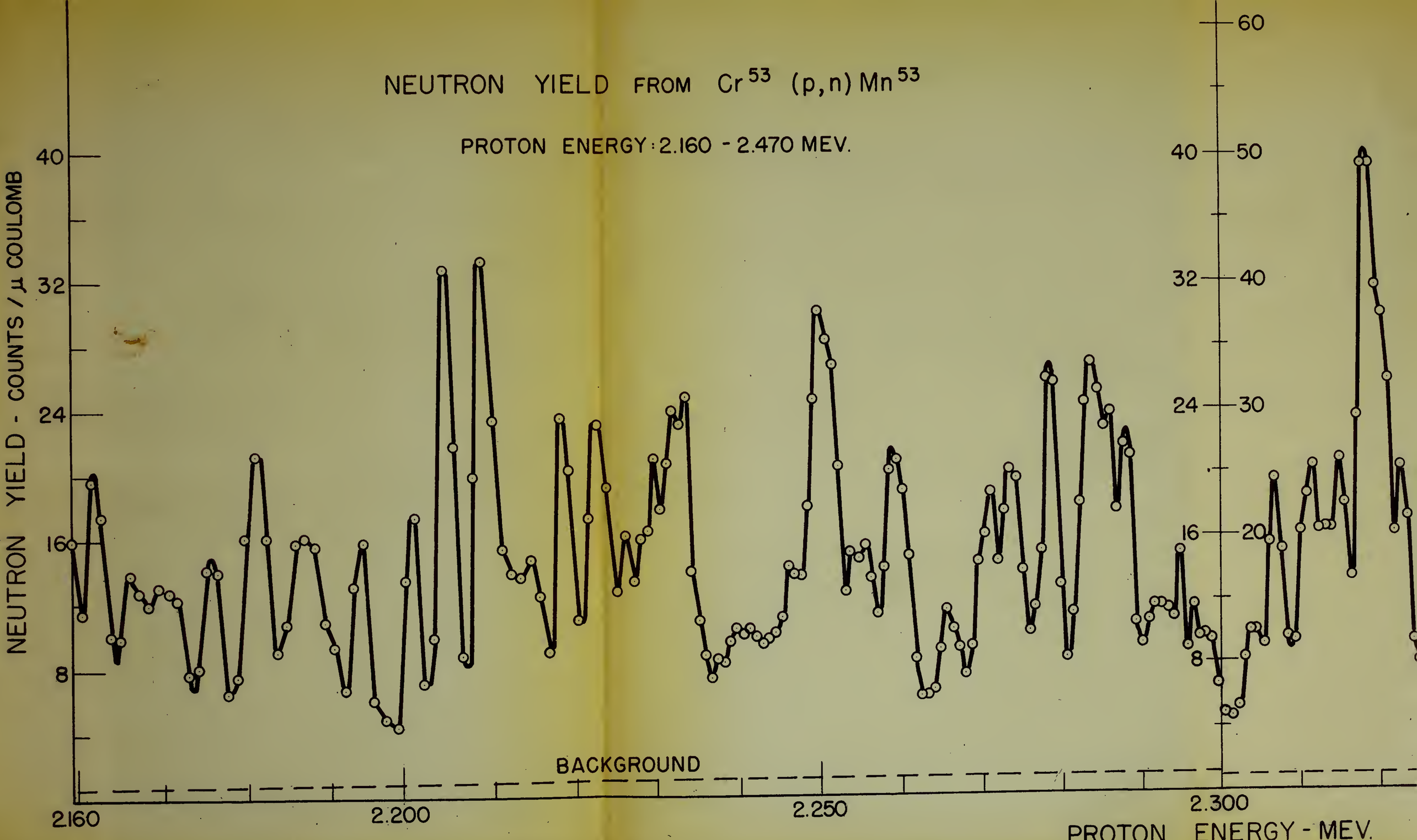


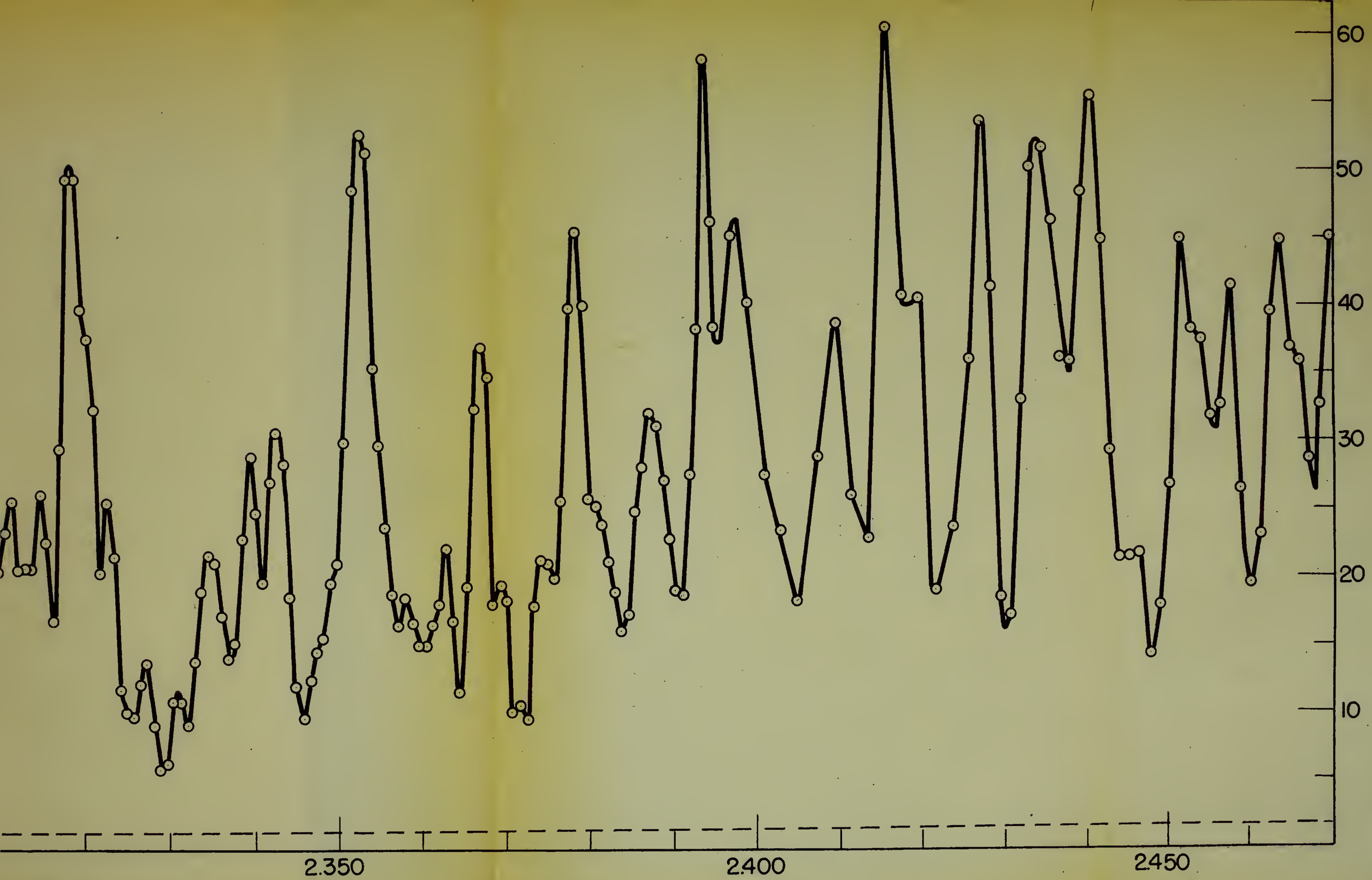


- MEV.

NEUTRON YIELD FROM Cr^{53} (p,n) Mn^{53}

PROTON ENERGY: 2.160 - 2.470 MEV.




60
50
40
30
20
10
2.350
2.400
2.450
- MEV.

Appendix B

NEUTRON YIELD FROM $Cr^{54}(p,n)Mn^{54}$

Proton Energy: 2.190-2.470 Mev.

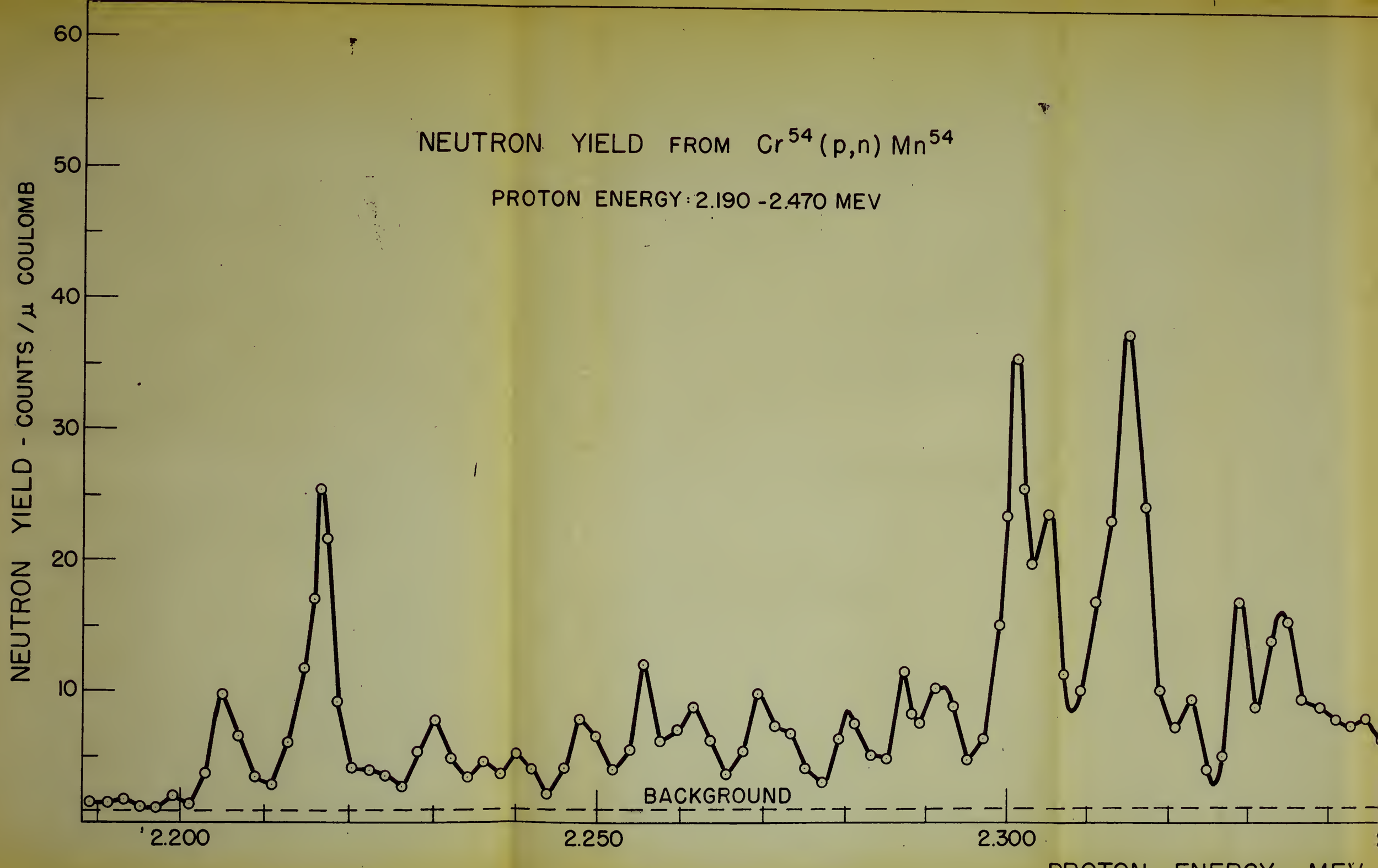
(1) 2.5 Kev target

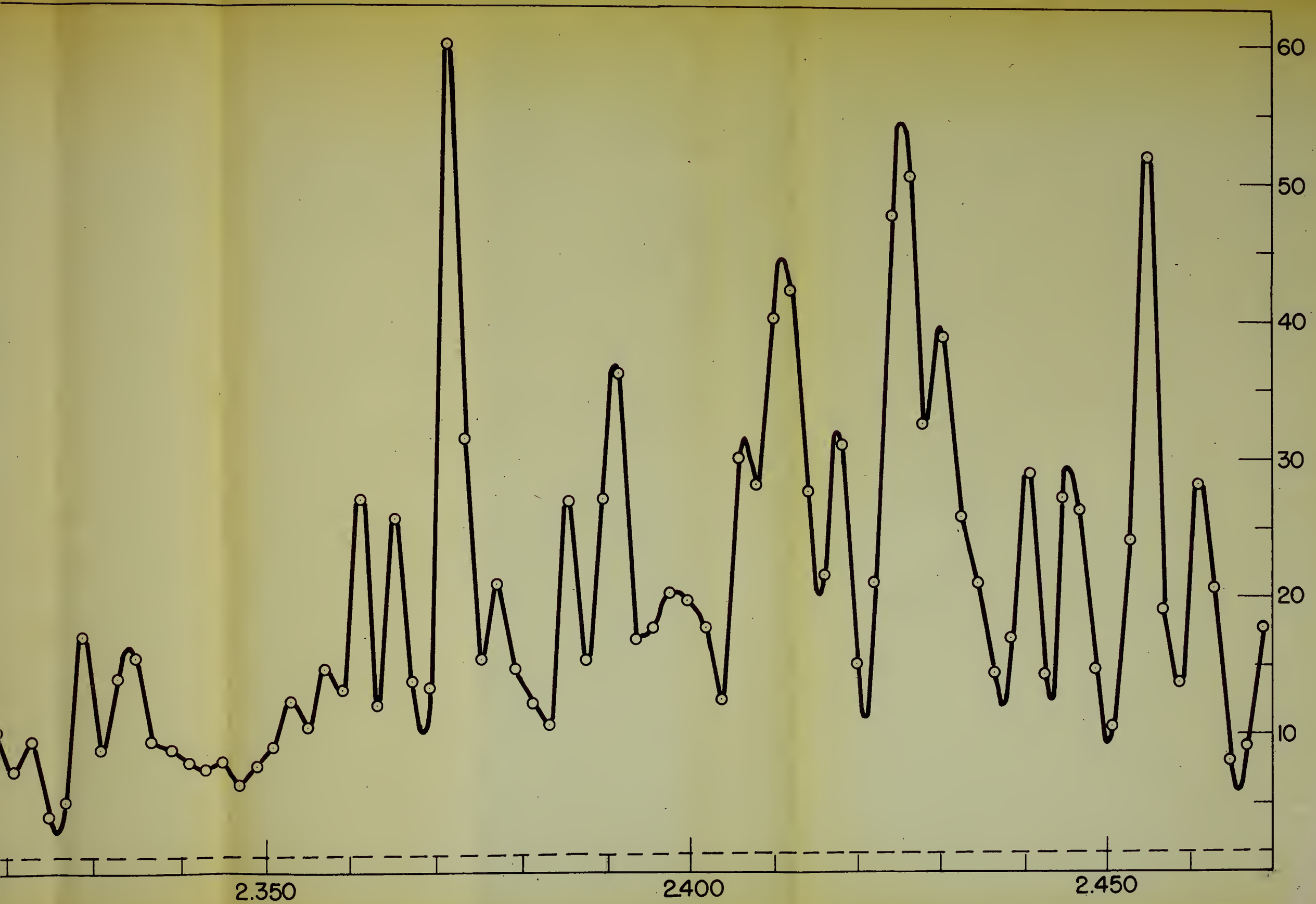
(2) 1.5 Kev target

Probable error is less than diameter of circles.

NEUTRON YIELD FROM $Cr^{54}(p,n)Mn^{54}$

PROTON ENERGY: 2.190 - 2.470 MEV

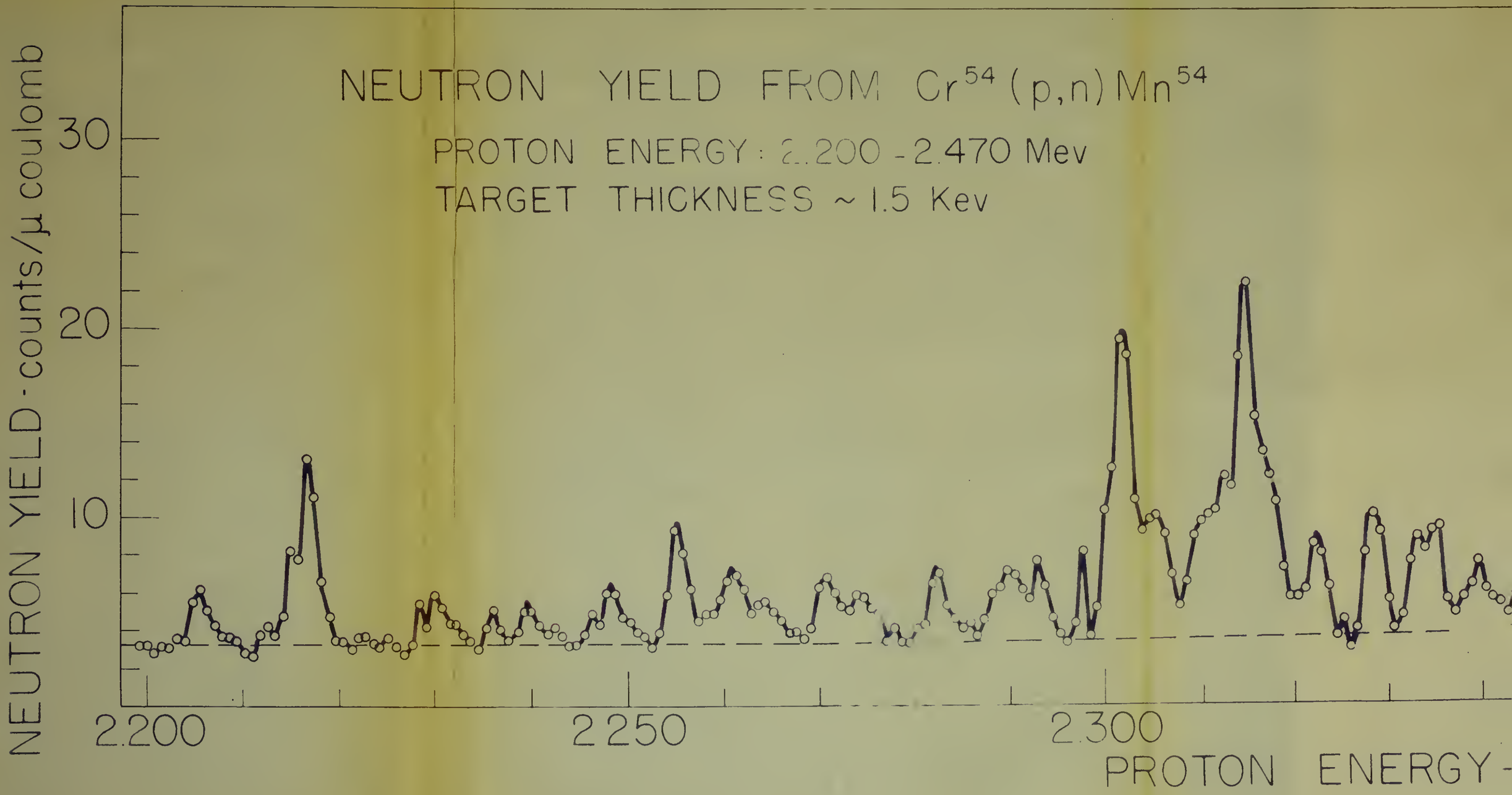


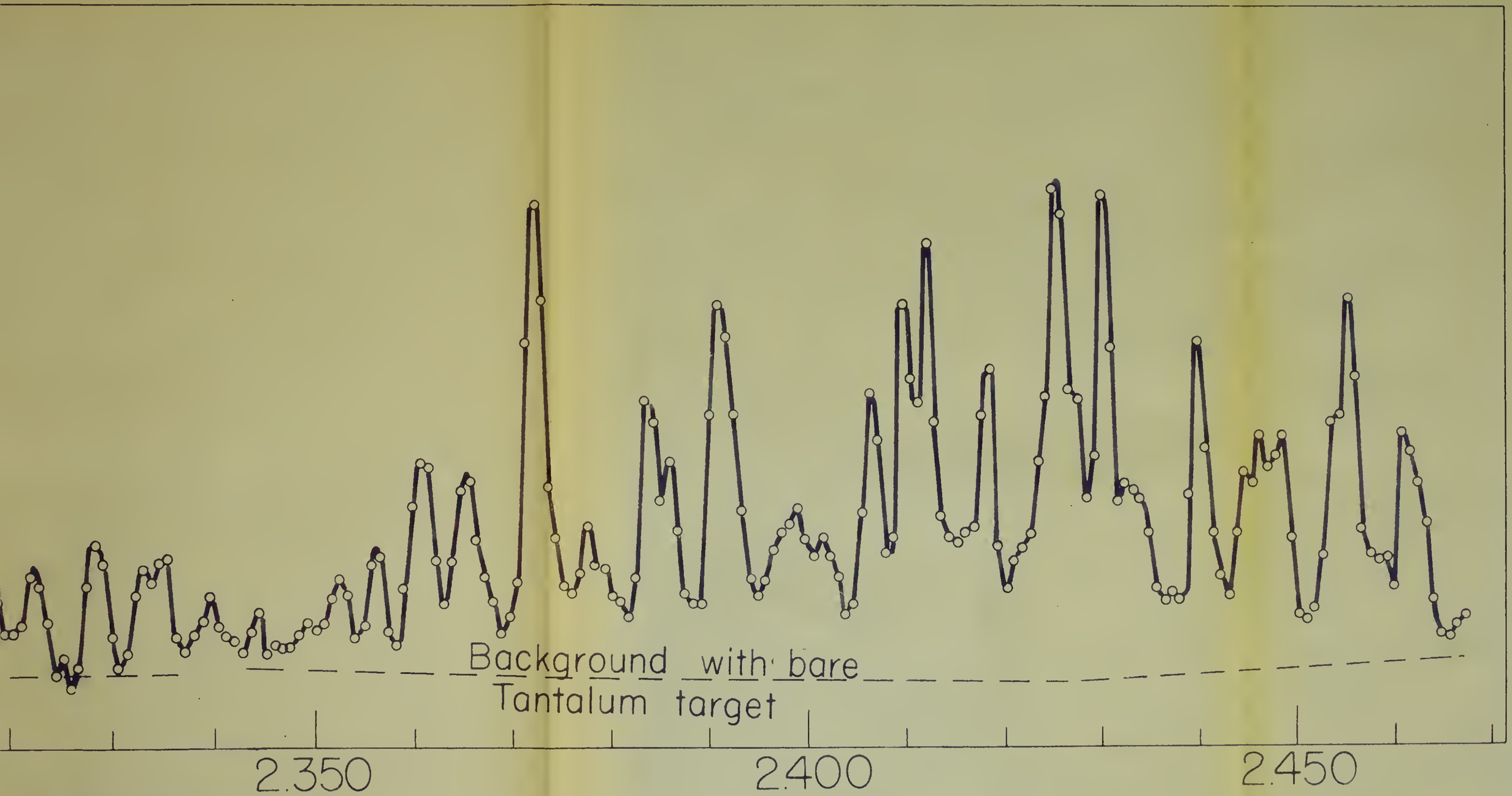

60
50
40
30
20
10
2.350
2.400
2.450
ENERGY - MEV.

NEUTRON YIELD FROM $Cr^{54}(p,n)Mn^{54}$

PROTON ENERGY : 2.200 - 2.470 Mev

TARGET THICKNESS ~ 1.5 Kev




Background with bare
Tantalum target
2.350
2.400
2.450
ENERGY - Mev.

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4678

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L853 Lovington
15640

Energy levels im medium weight nuclei from the (P,n) reaction.

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Energy levels in medium weight nuclei fr
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